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Published in:
17th International Conference on Industrial Informatics, INDIN 2019

DOI:
10.1109/INDIN41052.2019.8972137

Published: 01/01/2019

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Kuliaev, V., Atmojo, U. D., Sierla, S., Blech, J. O., & Vyatkin, V. (2019). Towards Product Centric Manufacturing: From Digital Twins to Product Assembly. In *17th International Conference on Industrial Informatics, INDIN 2019: Industrial Applications of Artificial Intelligence* (pp. 164-171). (IEEE International Conference on Industrial Informatics). IEEE. https://doi.org/10.1109/INDIN41052.2019.8972137

Towards Product Centric Manufacturing: From Digital Twins to Product Assembly

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***Abstract*—In product-centric manufacturing paradigm, a digital counterpart of a product will request manufacturing services to assemble itself. A modelling & assembly planning framework for product-centric design is considered and extended in this paper. Furthermore, we present a case-study on a product-centric digital twin controlling the assembly of its physical counterpart using a collaborative robot.**

Index Terms— Digital Twin; Product-Centric Manufacturing; Assembly; Industrial Robot; Industry 4.0.

I. Introduction

Industry 4.0, the fourth industrial revolution, is expected to bring about the dissolution of the well-established automation architecture [1-4]. It is based on the emerging Reference Architecture Model Industry 4.0 (RAMI 4.0), which promises real time availability of data and information over lifecycle phases and organizational boundaries [5]. Globally, RAMI 4.0 is considered a major reference architecture which competes with the US-driven Industrial Internet Consortium's IIRA (Industrial Internet Reference Architecture). Currently, mature technology in RAMI 4.0 is the OPC UA [6,7]. The counterpart of OPC UA in IIRA is DDS (Data Distribution Service) [8], which has been used in several cyber-physical production systems applications [9-11]. However, the body of research in RAMI 4.0 is more extensive than the literature on IIRA in the scientific field in general, and in the IEEE Industrial Electronics Society publication forums in particular, so in this paper, the terminology for previous research in RAMI 4.0 is used. In the context of RAMI 4.0, the focus so far has been on enabling technology, but the true revolution will occur when the technology is effectively exploited for the servitization of industry with advanced agile manufacturing paradigms executed by networked enterprises [3,12-14]. The need for agile manufacturing arises not only from rapidly changing market demand but also from novel product design approaches exploring larger parts of the design space [15] and the need to perform concurrent product design and assembly planning [16].

One example of an agile manufacturing-typed paradigm is the product-centric manufacturing. The revolutionary idea behind the product-centric manufacturing is that the digital counterpart of a product will request manufacturing services [17-23]. The benefit of product-centric manufacturing is that the manufacturing facility no longer requires offline assumptions about the types of products being manufactured, the kinds of operations required to manufacture each product order, and their order of executions. A stark contrast with the traditional practice, this results in potentially radical improvements in the capability to react to orders for increasingly personalized (customized) products in an agile fashion. However, the said publications focus on supply chain management and factory logistics.

Recent work has extended the product-centric manufacturing paradigm to the factory floor domain [24], demonstrating the concept in a self-made virtualized 3D environment. The extension of product-centric control to the factory floor level is accomplished by utilizing the emerging concept of the digital twin [25-27] of the product and the production resources. The digital twin is augmented with the capability for performing product centric manufacturing. The work in [24] is then extended to utilize OPC UA (Open Platform Communications Unified Architecture) to communicate the digital product description from the designer to one or more potential manufacturers [28], so that the designer and manufacturer may be of different organizations. However, this attempt so far goes only as far as virtual world (simulation). It lacks a comprehensive solution which covers the full lifecycle from digital product descriptions to "real", physical assembly.

This paper presents a new development that enables an integrated approach for product-centric manufacturing. The paper proposes a comprehensive solution which allows product-centric manufacturing in the factory floor and covers more comprehensive lifecycle from digital product descriptions to physical assembly. This paper is organized as follows. Section II provides some background information related to the product-centric manufacturing concept considered in the paper and the assembly planning and modelling framework. Section III describe presents an extension of the framework to integrate physical assembly. Section IV presents case studies which demonstrate the capabilities of the proposed framework, and Section V concludes the paper and points out some potential future works. In particular, the paper presents the following contributions:

- A full, extended framework developed on top of the one described in [24] with connection to physical assembly station on the factory floor.
- The implemented connection to a physical assembly of ABB IRB 14000 YuMi collaborative robot.
- Experimental results on using the framework to assemble lego-brick models in a product centric way.

II. Background

This section presents our overall concept and the existing planning and modeling framework which is used as a basis for our product centric manufacturing.

A. *Concept*

The product-centric manufacturing concept considered in this paper has 3 stages as illustrated in Figure 1:

1. Firstly, the original equipment manufacturer (OEM) designer sends a digital product description to one or more manufacturers, who will automatically and promptly perform a virtual assembly in a virtualized 3D production cell without any need for manual and physical engineering work. This has been achieved in a previous work for lego-block designs using collision detection (see [24] supplementary video 2) and for generic CAD part designs without collision detection (see [24] supplementary video 1). Based on the results of the virtual assembly, such as the above-mentioned video captures, the designer can assess, e.g., whether the design is practical and economical from the assembly perspective and if the manufacturer has suitable capabilities for manufacturing this design. The feedback can be used to modify the design and to narrow down the set of potential manufacturers. This stage can be rapidly repeated as often as needed.
2. In the second stage, the assembly is piloted with physical product parts and production equipment ("Pilot assembly"). For example, pilot assembly may involve Additive Manufacturing (AM), which is a potential technology for reducing the delays involved at this stage [29] especially due to overcoming the delays from the supply chain [30]. Although AM may not yet be a cost-effective technology for mass production [31-32], it is well suited for this stage in which pilots are needed to verify the results of the virtual assembly with a physical setup. In this case, all of the product parts might be 3D printed from their CAD files linked to the digital product description.
3. The third stage ("Ramp up") involves ramping up the production with the chosen manufacturer, after the design has been adjusted based on the results of the first two stages. The parts may continue to be produced with AM, a hybrid scenario which combines AM and conventional supply chain management [33], or even completely without AM.

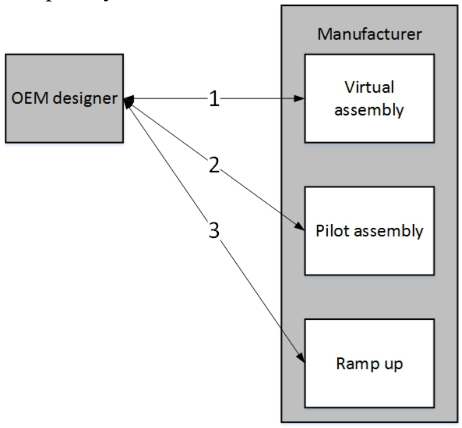


Figure 1. Stages of the product-centric manufacturing concept

In summary, the proposed concept could result in disruptive changes to how the manufacturing sector works, allowing innovative designers with small budgets to emerge, without needing to invest in dedicated production facilities. This can be made possible through the emergence of the versatile manufacturing facilities which can adhere to the concept as illustrated in Figure 1. However, only stage 1 of Figure 1 has been implemented in the previous research, consisting of a purely virtualized environment with considerable simplifying assumptions on the Cartesian robots that were used. A key challenge to be solved towards realizing stages 2 and 3 will be to adapt the methodology to include physical assembly, e.g., using physical robots with versatile capabilities.

B. *Assembly Planning and Modeling Framework*

This paper considers the assembly planning and modeling framework proposed in [24], which is claimed to enable plugging in more sophisticated ASP (Assembly Sequence Planning) and APP (Assembly Path Planning) algorithms to meet the specific needs of manufacturing cells, robots and products. So far, this framework has only been demonstrated in a self-made virtualized 3D environment with highly simplified Cartesian robots.

This paper considers the automatic assembly of products based on their digital product descriptions. In [28], products were created from workpieces/materials in the form of lego blocks and OPC UA address spaces were used for the product descriptions. A screenshot of an example product description of a "lego tower" on an OPC UA server is shown in Fig. 2. OPC UA types for square and rectangle legos have been defined with the appropriate connection points. legos are under a Parts folder. The screenshot from UaExpert shows one example design with several square and rectangle legos. In the Address space pane, the 'Color' attribute of the 'rect1' lego has been selected. In the Attributes pane, it can be seen that the value of this attribute is green.

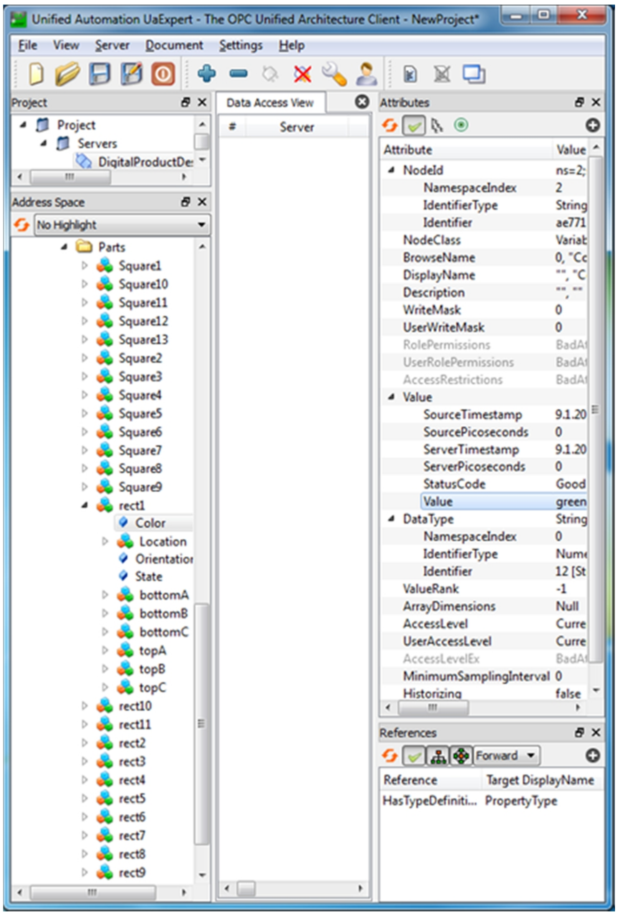


Figure 2: Product description of a "lego tower" as OPC UA information model

Based on the information in the product description, the methodology presented in [24] will automatically construct a digital twin of the final assembled product, using the 3D properties of the square and rectangle lego types as well as the connections between the legos in the product description. The digital twin is augmented with a product-centric control capability, including ASP and APP. The work demonstrated a product centric control using a virtual cartesian robot in a 3D virtual environment. In this environment, interconnected nodes are manipulated and the limitations, constraints and challenges of the physical world are ignored.

The following UML2 sequence diagram in Fig.3 presents the product-centric control for the stages 2 and 3 of Fig.1. This algorithm is executed cyclically, so each execution will exercise only a part of the code, according to the guard conditions in the opt, break and alt fragments. The function nextUnassembledPart() towards the bottom of the sequence is responsible for ASP. planAssemblyPath() is responsible for APP, returning a Trajectory object consisting of waypoints and rotations of the part to be assembled. The various Boolean variables are used to control the translational movement to the next waypoint or the rotation.

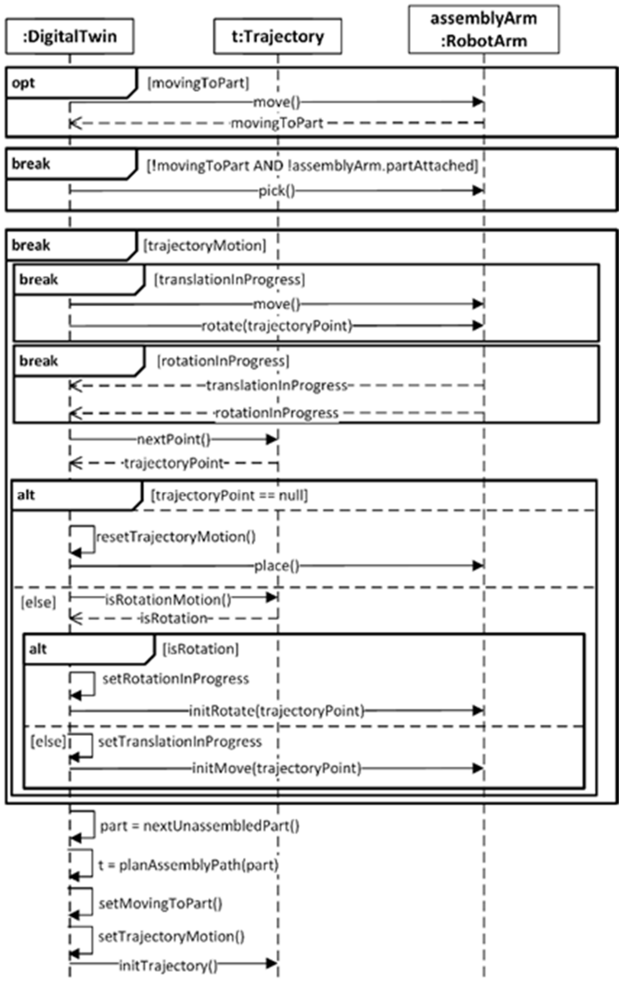


Figure 3: Product Centric Assembly Requests

When the translation or rotation has accomplished, the sequence proceeds to call the nextPoint() method of the Trajectory object. If this returns null, the sequence will go to the place() method and proceed to the next call of ASP. In this paper, this sequence has been implemented on a PC machine that hosts the digital twin and communicates with a physical assembly station (ABB IRB14000 YuMi robot) through socket in order to realize the product centric manufacturing in the physical world.

III. Product Centric Control in a Physical Assembly Cell

In this section, the product centric control is implemented and interfaced to resources in the physical assembly cell. The overall architecture of the proposed solution is shown in Fig.4.

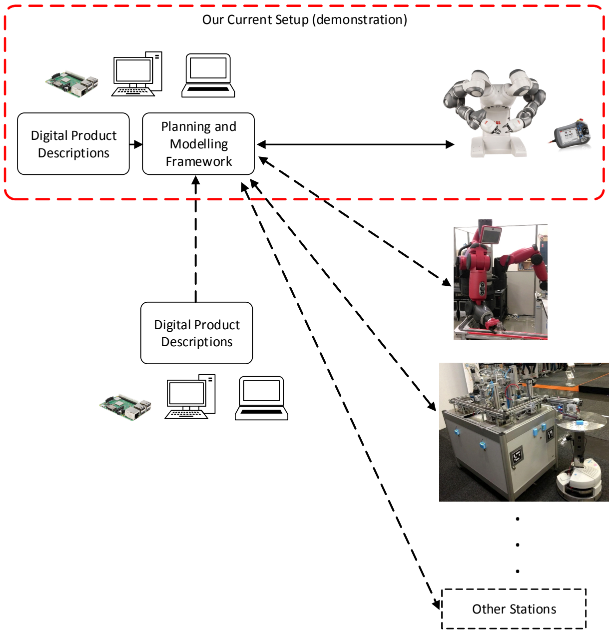


Figure 4: Digital Twin on a PC Controlling Production Stations.

A. *Assembly Planning/Modelling Framework Side*

The framework described in Section 2 is implemented in Java and may run on various computing platforms, e.g., PC. Based on the given digital product descriptions, the framework automatically generates several information regarding the workpiece. This includes the type of the workpiece, the name/identification of the workpiece, the three axis coordinates of where the workpiece should be placed (the target location) through the mechanism described in Section 2, and whether it requires the workpiece to be rotated for 90 degrees. This information needs to be transferred to the physical assembly station.

To achieve the aforementioned goal, some improvements had to be made to the framework described in the previous section, in particular:

- Introduce communication interface: The information generated by the planning/modelling framework needs to be transmitted to physical station controller on the factory floor, so this communication interface needs to be introduced. At this stage, this communication interface is realized through TCP/IP communication socket which is available in many execution/controller platforms, including in Java environment (which the planning/modelling framework is implemented in currently). In the next development stage, this could easily be replaced with standardized communication protocol in automation, e.g., OPC UA in a client-server model.
- A messaging protocol is introduced between the framework and the physical station controllers. This includes the message to start, message which contains the information generated by the planning/modelling framework, and finish the robot program execution. The information from the planning/modelling framework is appended together as one message to simplify the protocol.
- Actuator coordination (in our particular case, e.g. the rotation of workpiece) functionality in the DigitalTwin class underwent changes to make the message structure more compact.

B. *Physical Assembly Side*

In general, physical assembly stations can have different hardware controllers (e.g., PLCs of different vendors) with different software environments and actuators. Our physical setup is illustrated in Fig. 4 inside the red-dashed area. In this setup, the physical assembly actor corresponds to one ABB IRB 14000 Dual Arm Precision “YuMI” robot. The YuMI robot is based on IRC5 controller and relies on RAPID programming language environment. Thus in this case, the robot control software logic is implemented using RAPID language. To implement the robot control software logic in this scenario, the following components/functionalities have been realized:

1. Calibration. In our scenario, this involves the calibration of the YuMI’s gripping fingers’ arm, which is necessary for the robot software control logic. This calibration is done to obtain the absolute position of the YuMI’s gripper when it is opening and closing.
2. Initialization. This function which is responsible for opening the network communication socket and waiting for the message containing a “Start” message. Upon receiving the Start message, the control logic actuates both YuMI’s arm to move them to a “safe” position according to the YuMI technical documentations. The safe position is required as collision avoidance is turned off for pushing the blocks together.
3. The following describes the entire software control logic for assembling the product out of workpieces. The program is presented as a recurring loop, which consists of the following:
   - Execute the “Initialization” function. This function actuates YuMI’s arms to the initial (safe) position, if they are not in such position yet.
   - Communication to transmit and receive message. This communication is achieved through socket. Unfortunately, the RAPID programming language supports less data types compared to Java, however the language supports string and byte formats which are also available in Java. Here, the string format is chosen since it can be used to transmit information of different “nature” from simple numbers to words. Byte format was also an option, however the byte format of the message is more difficult to make sense for development

purpose

- Separation of the message to extract different information included in the message, which includes type of the workpiece, ID of the workpiece, whether the workpiece needs to be rotated for assembly, and the three axis coordinates of the workpiece at the final location of assembly.
- Actuate the YuMI arm to approach the correct workpiece, actuate the gripper to grab and pick the correct workpiece using its gripper, and then move the arm towards the target location as determined by the three axis coordinates via safe trajectories, and then place the workpiece on the target location.
- Pushing the workpiece on the assembly position. In this case study, the pushing is necessary since the case study involves workpiece in the form of lego blocks. This pushing will ensure that the workpiece is attached firmly to the assembly position. This pushing action is performed by gentle pressing on the workpiece. The pushing action is performed twice to ensure that the workpiece has been attached properly.
- Robot arms returns to the initial ("safe") position before it can receive the next command to pick and assemble the next workpiece.

4. Completion: The control logic checks if the "Stop" message was received. When this message is received, the robot moves both arms to the safe position. When the arms have reached the safe position, will then robot can be transported to some other location if needed.

The robot software control logic can be presented as a flowchart shown in Fig.5.

IV. CASE STUDIES

To demonstrate the capability and the agility of the proposed solution in assembling customized products, two case studies of assembly planning & execution are considered.

The digital product descriptions in OPC UA are not intended for the human reader, so in this section they are represented in a different format as follows. The relevant information has been extracted from the digital product descriptions and then presented in two tables. The first table includes the information typically present in a BOM (Bill of Materials) as well as the angle of orientation of the part/workpiece during assembly. The second table presents the connections between the workpieces ("connection configuration"). It's important to note that the case studies consider lego blocks as workpieces. A rectangle lego has three "connection" points in our case studies, to which another lego block can be connected to.

Every connection points represents the center of the 4x2 studs of the lego block , and in the case of 4x2 studs lego block, each connection point has interleaving 2x1 studs with the adjacent connection point. The three connection points on the top surface are referred as topA, topB, topC. Meanwhile on the bottom, lego block has connections points bottomA, bottomB and bottomC. The information provided in both tables is sufficient to determine the coordinates of where each workpieces/lego blocks will be moved to during assembly, and the information is used to generate ASP and APP by the assembly planning and modelling framework.

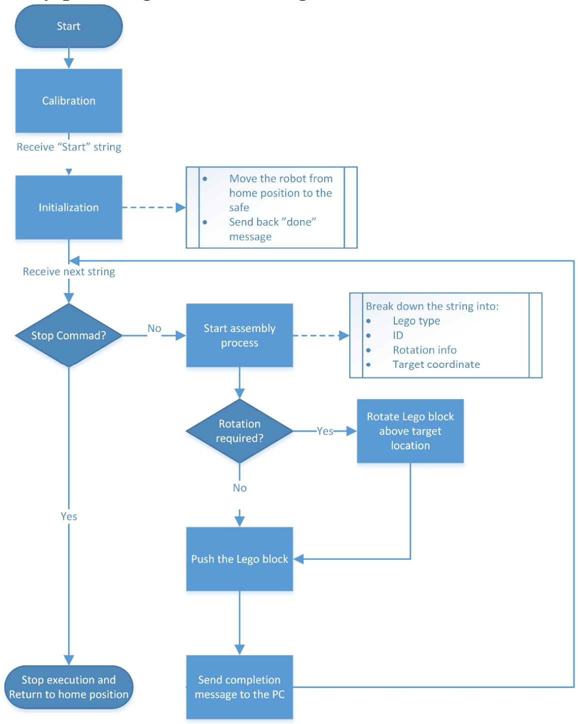


Figure 5. Flowchart of the robot software control logic

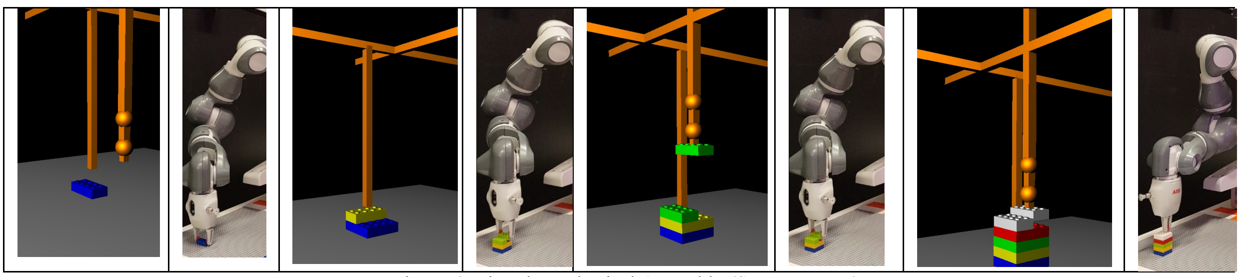


Figure 6. Virtual vs. Physical Assembly (Square Tower).

For the purpose of description, the case studies will be referred as “Square Tower” and “Pyramid Tower”.

A. *Case Study 1 “Square Tower”*

The Square Tower is assembled from 10 lego blocks and has a square shape with the same number of lego blocks on each stack. The product descriptions of the Square tower are presented in Table 1 (it’s “BOM” and angle of orientation) and Table 2 (it’s “connection configuration”).

TABLE 1 SQUARE TOWER PART LIST

Type	Part id	Color	Orientation
RectangleLego	Rectan1	blue	90
RectangleLego	Rectan2	yellow	0
RectangleLego	Rectan3	blue	90
RectangleLego	Rectan4	yellow	0
RectangleLego	Rectan5	green	90
RectangleLego	Rectan6	green	90
RectangleLego	Rectan7	red	0
RectangleLego	Rectan8	red	0
RectangleLego	Rectan9	white	90
RectangleLego	Rectan10	white	90

The parts used to assemble Square Tower has the same type (RectangleLego), with various colors and orientations. How these parts are connected is described in Table 1.

TABLE 2 FIRST TOWER CONNECTION LIST

Connection endpoint 1		Connection endpoint 2	
Part id	**Connection point**	**Part id**	**Connection point**
Rectan2	bottomA	Rectan1	topA
Rectan2	bottomC	Rectan3	topA
Rectan1	topC	Rectan4	bottomA
Rectan5	bottomA	Rectan2	topA
Rectan6	bottomA	Rectan2	topC
Rectan7	bottomA	Rectan5	topA
Rectan8	bottomA	Rectan5	topC
Rectan9	bottomA	Rectan7	topA
Rectan10	bottomA	Rectan7	topC

The planning/modelling framework generates new information which is then sent to the YuMI robot for the assembly of Square Tower. Some snapshots of the physical assembly of the Square Tower and its digital counterpart is shown in Fig.6.

B. *Case Study 2 “Pyramid Tower”*

This Pyramid Tower case study is similar to the Square Tower, in a sense that it uses the same number of lego blocks (10 lego blocks). However, the main difference is that the Pyramid Tower has a pointed tip (I.e., only has one lego block at the top most stack), which is not the case for Square Tower, and the bottom stack of the Pyramid Tower uses more lego blocks than the Square Tower. The product descriptions of the Pyramid Tower are presented in Table 3 and Table 4.

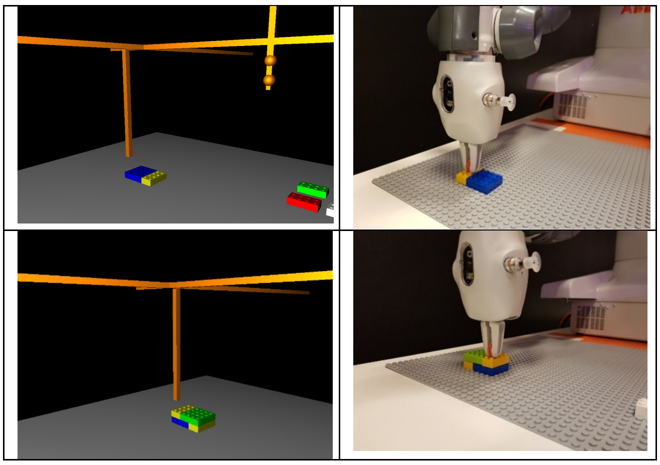
TABLE 3 PYRAMID TOWER PART LIST

Type	Part id	Color	Orientation
RectangleLego	Rectan1	blue	90
RectangleLego	Rectan5	blue	90
RectangleLego	Rectan2	green	90
RectangleLego	Rectan3	yellow	0
RectangleLego	Rectan4	green	90
RectangleLego	Rectan6	yellow	180
RectangleLego	Rectan7	red	0
RectangleLego	Rectan8	red	0
RectangleLego	Rectan9	white	90
SquareLego	Square1	white	-

Based on the product description, the planning/modelling framework generates the information to be sent to the YuMI robot. Some snapshots of physical assembly and its digital counterpart are shown in Fig.7. As an additional note, the top most stack of the Pyramid Tower uses 2x2 studs lego block (referred as SquareLego) instead of 4x2 studs lego block.

TABLE 4 PYRAMID TOWER CONNECTION LIST

Endpoint 1		Endpoint 2	
Part id	**Conn. point**	**Part id**	**Conn.point**
Rectan2	bottomA	Rectan1	topC
Rectan2	topC	Rectan3	bottom
Rectan1	topC	Rectan4	bottomA
Rectan5	topC	Rectan4	bottomA
Rectan6	bottomA	Rectan5	topA
Rectan7	bottomA	Rectan2	topA
Rectan8	bottomA	Rectan2	topC
Rectan9	bottomA	Rectan7	topB
Square1	bottom	Rectan9	topB



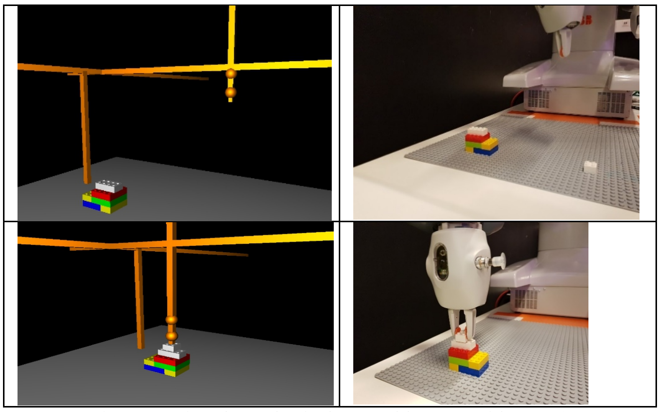


Figure 7. Virtual vs. Physical Assembly (Pyramid Tower)

V. Conclusions

This paper proposed a framework for product-centric design so that it connects to manufacturing devices. Here, a digital counterpart of a product requests manufacturing services to assemble itself. In a concrete realization, a digital twin controls the assembly of its physical counterpart by communicating with ABB's YuMi collaborative robot.

Future work will feature more generalized production steps such as transportation of work-pieces between production islands and the control of these production islands through digital twins. Furthermore, there is an interest particularly to connect digital twins to visualization platforms [34]. Formal modeling and reasoning about digital twins, e.g., for safety and collision avoidance similar to the work in [35] is also a topic for the future. More accurate 3D models of the manufacturing equipment is a goal for the very near future, this should also allow for a more precise collision avoidance. The aspect of dynamicity is also worth investigating, e.g., similar to the work in [36] [37].

References

[1] V. Krueger, A. Chazoule, M. Crosby, A. Lasnier, M.R. Pedersen, F. Rovida, L. Nalpantidis, R. Petrick, C. Toscano, G. Veiga, A Vertical and Cyber–Physical Integration of Cognitive Robots in Manufacturing," in Proceedings of the IEEE, vol. 104, no. 5, pp. 1114-1127, 2016.

[2] R. Harrison, D. Vera and B. Ahmad, "Engineering Methods and Tools for Cyber–Physical Automation Systems," in Proceedings of the IEEE, vol. 104, no. 5, pp. 973-985, 2016.

[3] H. Kagermann, R. Anderl, J. Gausemeier, G. Schuh, W. Wahlster (Eds.): “Industrie 4.0 in a Global Context: Strategies for Cooperating with International Partners” (acatech STUDY), Munich: Herbert Utz Verlag 2016.

[4] A.J. Isaksson, I. Harjunkoski, G. Sand, “The impact of digitalization on the future of control and operations”, Computers & Chemical Engineering, Volume 114, Pages 122-129, 2018.

[5] F. Zezulka, P. Marcon, I. Vesely, O. Sajdl, “Industry 4.0 – An Introduction in the phenomenon”, IFAC-PapersOnLine, vol. 49, no. 25, pp. 8-12, 2016.

[6] S. Grüner, J. Pfrommer, F. Palm, “RESTful Industrial Communication With OPC UA”, IEEE Transactions on Industrial Informatics vol. 12, no. 5, 1832-1841, 2016.

[7] V. Jirkovský, M. Obitko, P. Kadera, V. Mařík, “Toward Plug&Play Cyber-Physical System Components”, IEEE Transactions on Industrial Informatics, vol. 14, no. 6, 2803-2811, 2018.

[8] P. Marcon, F. Zezulka, I. Vesely, Z. Szabo, Z. Roubal, O. Sajdl, E. Gescheidtova, P. Dohnal, “Communication technology for industry 4.0”, Progress In Electromagnetics Research Symposium - Spring (PIERS). St. Petersburg, 22-25 May 2017, pp. 1694-1697.

[9] A. Bonci, M. Pirani, S. Longhi, “A database-centric approach for the modeling, simulation and control of cyber-physical systems in the factory of the future”, IFAC-PapersOnLine, vol. 49, no. 12, pp: 249-254, 2016.

[10] P. Peniak and M. Franekova, “Open communication protocols for integration of embedded systems within Industry 4”, 2015 International Conference on Applied Electronics (AE). Pilsen, Czech Republic, 8-10 Sep 2015, pp. 181-184.

[11] M. García-Valls, C. Calva-Urrego, J.A. de la Puente, A. Alonso, “Adjusting middleware knobs to assess scalability limits of distributed cyber-physical systems”, Computer Standards and Interfaces, vol. 51, pp: 95-103, 2017.

[12] J. Huxtable, D. Schaefer, “On Servitization of the Manufacturing Industry in the UK”, Procedia CIRP, vol. 52, pp: 46-51, 2016.

[13] A. Fayoumi, “Ecosystem-inspired enterprise modelling framework for collaborative and networked manufacturing systems”, Computers in Industry, vol. 80, pp: 54–68, 2016.

[14] A. Giret, E. Garcia, V. Botti, “An engineering framework for Service-Oriented Intelligent Manufacturing Systems”, Computers in Industry, vol. 81, pp: 116–127, 2016.

[15] D. Bacciotti, Y. Borgianni, F. Rotini, An original design approach for stimulating the ideation of new product features, Computers in Industry, vol. 75, pp: 80–100, 2016.

[16] E. Gruhier, F. Demoly, S. Gomes, “A spatiotemporal information management framework for product design and assembly process planning reconciliation”, Computers in Industry, vol. 90, pp: 17–41, 2017.

[17] J. Lyly-Yrjänäinen, J. Holmström, M.I. Johansson, P. Suomala, “Effects of combining product-centric control and direct digital manufacturing: The case of preparing customized hose assembly kits”, Computers in Industry, vol. 82, pp: 82–94, 2016.

[18] D. McFarlane, S. Sarma, J.L. Chirn, C. Wong, K. Ashton, “Auto ID systems and intelligent manufacturing control”, Engineering Applications of Artificial Intelligence, vol. 16, no. 4, pp: 365–376, 2004.

[19] G. Meyer, J. Wortmann, N. Szirbik, “Production monitoring and control with intelligent products”, International Journal of Production Resources, vol. 49, no. 5, pp: 1303–1317, 2011.

[20] J. Holmström, A. Tenhiälä, M. Kärkkäinen , “Item dwell time in project inventories: A field experiment”, Computers in Industry, vol. 62, no.1, pp: 99-106, 2011.

[21] M. Rönkkö, M. Kärkkäinen, J. Holmström, “Benefits of an item-centric enterprise-data model in logistics services: a case study”, Computers in Industry, vol. 58, no. 8, pp: 814–822, 2017.

[22] J.F. Pétin, D. Gouyon, G. Morel, “Supervisory synthesis for product-driven automation and its application to a flexible assembly cell”, Control Engineering Practice, vol. 15, no. 5, pp: 595–614, 2007.

[23] A. Musa, A. Gunasekaran, Y. Yusuf, “Supply chain product visibility: methods, systems and impacts”, Expert Systems with Applications, vol. 41, no. 1, pp: 176–194, 2014.

[24] S. Sierla, V. Kyrki, P. Aarnio, V. Vyatkin, “Automatic assembly planning based on digital product descriptions”, Computers in Industry, vol. 97, pp. 34–46, 2018.

[25] K. M. Alam and A. El Saddik, "C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems," IEEE Access, vol. 5, pp. 2050-2062, 2017.

[26] M. Schluse, L. Atorf and J. Rossmann, "Experimentable digital twins for model-based systems engineering and simulation-based development," 2017 Annual IEEE International Systems Conference (SysCon), Montreal, QC, 2017, pp. 1-8.

[27] G. Schroeder, C. Steinmetz, C.E. Pereira, I. Muller, N. Garcia, D. Espindola, R. Rodrigues, Visualising the digital twin using web services and augmented reality, 2016 IEEE 14th International Conference on Industrial Informatics (INDIN) Pages: 522 – 527

[28] M. Yli-Ojanperä, S. Sierla, N. Papakonstantinou, V. Vyatkin, (2018) Adapting an Agile Manufacturing Concept to the Reference Architecture Model Industry 4.0: a survey and case study, Journal of Industrial Information Integration, Available online 25 December 2018

[29] M. Attaran, “The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing”, Business Horizons, vol. 60, no. 5, pp: 677-688, 2017.

[30] S.H. Khajavi, J. Partanen, J. Holmström, "Additive manufacturing in the spare parts supply chain", Computers in Industry, vol. 65, pp. 50-63, 2014.
[31] Q. Li, I. Kucukkoc, D.Z. Zhang, "Production planning in additive manufacturing and 3D printing", Computers & Operations Research, vol. 83, pp. 157-172, 2017.
[32] R. F. Hartl, P.M. Kort, "Possible market entry of a firm with an additive manufacturing technology", International Journal of Production Economics, vol. 194, pp: 190-199, 2017.
[33] S.H. Khajavi, J. Partanen, J. Holmström, J. Tuomi, "Risk reduction in new product launch: A hybrid approach combining direct digital and tool-based manufacturing", Computers in Industry, vol. 74, pp. 29-42, 2015.
[34] I. Peake, J.O. Blech, L. Fernando, H. Schmidt, R. Sreenivasamurthy, S.D. Sudarsan, (2015, September). Visualization facilities for distributed and remote industrial automation: VxLab. In 2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA) pp. 1-4.
[35] J.O. Blech, P. Herrmann, I. Peake, H. Schmidt, (2015, April). Towards a model-based toolchain for remote configuration and maintenance of space-aware systems. In 2015 International Conference on Evaluation of Novel Approaches to Software Engineering (ENASE) pp. 331-336.
[36] Z. Salcic, U. D. Atmojo, H. Park, A. T. Chen and K. I. Wang, "Designing Dynamic and Collaborative Automation and Robotics Software Systems," in *IEEE Transactions on Industrial Informatics*, vol. 15, no. 1, pp. 540-549, Jan. 2019. doi: 10.1109/TII.2017.2786280
[37] U. D. Atmojo, Z. Salcic and K. I. Wang, "Dynamic Reconfiguration and Adaptation of Manufacturing Systems Using SOSJ Framework," in *IEEE Transactions on Industrial Informatics*, vol. 14, no. 6, pp. 2353-2363, June 2018. doi: 10.1109/TII.2018.2808270